# 2.0 Background Theory

Before analyzing how oscillating flaps can benefit flight characteristics, such as lift coefficient, it is imperative to provide the background theory necessary for the development and understanding of this project. First, basic aerodynamic forces are discussed; after which, the background behind lift-enhancing devices is discussed; this is followed by a brief explanation on flutter. Limit Cycle Oscillation (LCO) information is discussed as well, in regards to how it affects the aerodynamic forces. Lastly, information on oscillating flaps is discussed.

There are four aerodynamic forces associated with flying objects; they are thrust, lift, drag, and weight. The scope of this project is to investigate the effects of oscillating flaps on lift. Lift and drag are two essential forces associated with flight; however, lift is the only essential force necessary for flight.

When an aircraft is in flight, air flows around the airfoil and creates two different velocity regions along the top and bottom surfaces of the wing.

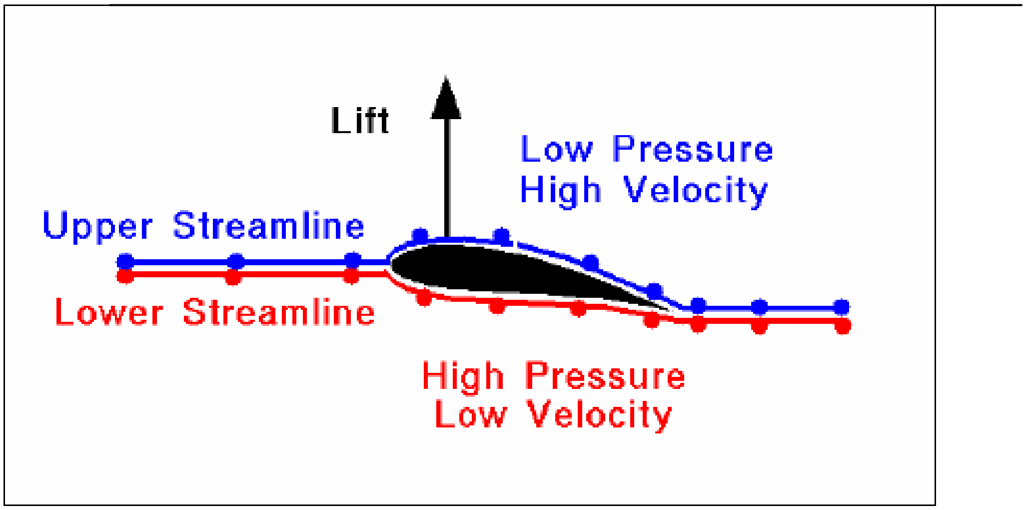


**Figure 2.1: Relationships between velocity and pressure [4]**

As seen in Figure 2.1, when air molecules approach an airfoil, the molecules that flow over the top speed up; this yields a high velocity region along the top surface when compared to the velocity region along the bottom surface.

Based on the equation

$$P + \frac{1}{2}\rho V^2 + \rho g h = const \;\; [4] \qquad \text{Eq. 2.1}$$

from Bernoulli's principle, it can be seen that as the velocity increases, the pressure must decrease along the top surface of the aircraft wing. This occurs vice versa in regards to the bottom surface of the aircraft wing, assuming that the variations of air density ( $\rho$ ), gravitational force (g), and altitude are negligible when in constant altitude flight. This phenomenon implies that the bottom surface of the wing experiences a high-pressure region and the top surface experiences a low-pressure region. This pressure gradient generates an upward force perpendicular to the surface of the wing, providing a lift. The aerodynamic force, lift, can be defined by the equation below:

$$L = \frac{1}{2} C_L \rho S V^2 \;\; [5] \qquad \text{Eq. 2.2}$$

where, air density at local altitude is denoted as $\rho$, $S$ is the wing area, $C_L$ is the coefficient of lift, and $V$ is the velocity of flight through the air. The amount of lift generated by the wing depends on the shape of the cross-section of the airfoil and the inclination with respect to the flow direction. The inclination of the wing with respect to the flow is cited as the angle of attack, also described as the angle between the chord line of the airfoil and the flow direction. Studies have implemented and stated that the amount of lift can be increased by increasing the angle of attack. The lift varies almost linearly for small angles of attack (within +/- 10 degrees) [6]. For higher angles of attack, however, the increase in angle of attack has a negative effect on the lift. As described above, the air molecules stick to the surface of the wing as it moves through the air, which creates a layer of air near the surface of the wing, called a boundary layer. When an aircraft flies at a critical angle of attack, the boundary layer detaches from the surface of the wing and the flow becomes turbulent, which causes the aircraft to dramatically loose lift and stall.

Lift coefficient is generally used to model all of the complex dependencies of shape, inclination, and flow conditions on lift. Lift analysis can be simplified by analyzing lift coefficient alone, which is governed by the equation below:

$$C_L = \frac{L}{0.5\rho V^2} \text{ [5]} \qquad \text{Eq. 2.3}$$

Generally speaking, lift coefficient is a nondimensional value and dependent to the angle of attack and the cross-section shape of the airfoil. The relationship between lift coefficient and angle of attack can be expressed by the $C_L$ vs. Angle of Attack plot below, which was obtained from several experiments. [7]

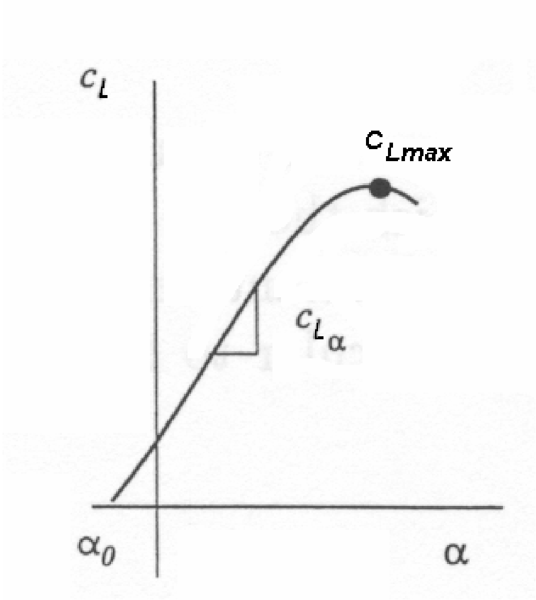


**Figure 2.2: Relationship Between Lift coefficient and Angle of Attack $\alpha$ [6]**

As seen from the plot, the lift coefficient has a linear relationship with the angle of attack. However, when the lift coefficient reaches the maximum value, which is at the critical angle of attack, it starts to decrease if the angle of attack continues to increase. When the lift coefficient passes the maximum value, the aircraft starts to stall due to the separation of the boundary layer from the top surface of the wing. The velocity at which the aircraft stalls, $V_{Stall,}$ is defined by the equation below:

$$V_{Stall} = \sqrt{\frac{2W}{S\rho C_{L\max}}} \text{ [4]} \qquad \text{Eq. 2.4}$$

where the weight of the aircraft is denoted as $W$, and the maximum value of lift coefficient is denoted as $C_{L\max}$. The stall speed determines the minimum airspeed an aircraft can fly to have a sufficient amount of lift in order to sustain the weight of the aircraft during unaccelarated flight. In the design process, weight is minimized, and the lift coefficient is the ideal parameter to optimize in order to reduce the stall speed. When an aircraft lands on an aircraft carrier, it wants to slow down, so the nose is pitched up, and the flaps are deflected down to decrease the aircraft's speed and to gain a sufficient amount of lift in order to sustain the aircraft's weight. If the angle of attack is increased to a critical value, there is a possibility that the aircraft will stall. Therefore, techniques have been used in order to increase the lift coefficient, and thus obtain more lift.

## *2.1 Lift-Enhancing Devices*

Leading and trailing-edges flaps and slats are used to increase lift coefficient. Figure 2.3, found below, is an example of how flaps are used during different flying conditions. The flaps change the pressure distribution on the airfoil due to the increase in chord length and camber. In addition, the flaps increase the area of the wing perpendicular to the airflow direction in order to increase lift and decrease the stall speed. Newtonian approach and Thin Airfoil Theory can be used to describe how increasing the camber has the possibility of increasing the lift. "The Newtonian approach states that lift is the result of pressure reactions that oppose the turning of flow, thus higher lift is caused by greater turning." [4] Notice from Figure 2.3, the flap deflection angle at takeoff is smaller than at landing.

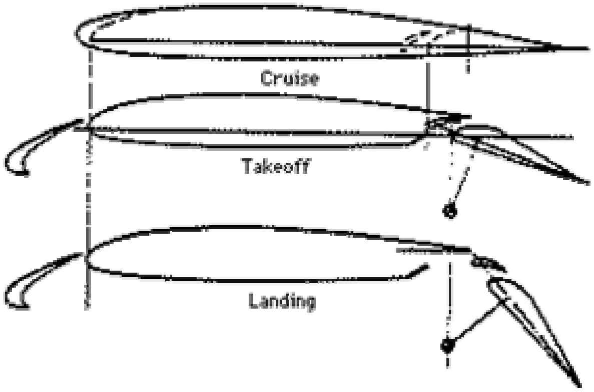


**Figure 2.3: Flap Deflection During Different Flight Conditions [6]**

At zero angle of attack, the Thin Airfoil Theory describes the camber effects on lift using the equation below:

$$C_L = 2\pi\alpha_{3/4} \text{ [4]} \qquad \text{Eq. 2.5}$$

where $\alpha_{3/4}$ is the angle between the chord axis and the line tangent to the airfoil as seen from Figure 2.3.

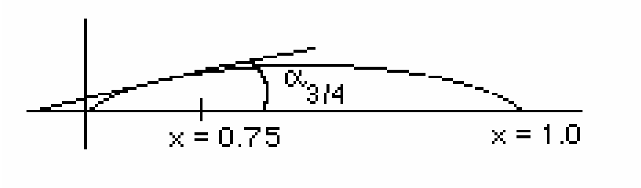


**Figure 2.4: Thin Airfoil Example [7]**

As the camber increases, the angle $\alpha_{3/4}$ also increases, and thus the lift coefficient increases as well. Slats are used as an opening at the leading edge of the airfoil to allow high pressure air underneath the airfoil to combine with the air on the top surface of the wing, which increases the energy of the boundary layer. "By increasing the energy of the boundary layer, the wing can sustain higher angles of attack and a higher maximum coefficient of lift." [8] Figure 2.5 is an example of a slat that is located at the leading edge of the airfoil.

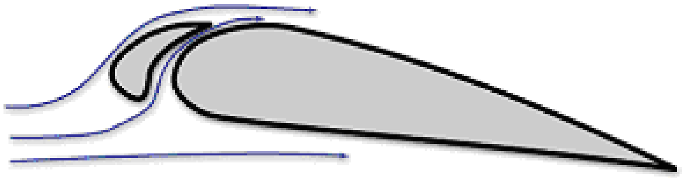


**Figure 2.5: Airflow Through Slat in Airfoil [9]**

## *2.2 Flutter*

Aircraft wings are flexible and easily to bend or twist during flight due to the pressure of the airflow acting on the structure; however, aircraft wings are designed to withstand high loads. During high speed flights, the static air loads can cause the wing tips to flap or oscillate in a periodic manner. As the speed increases, the air loads continue feeding the elastic motion of the wing and increases the oscillation amplitude, thus increasing the air loads, which eventually exceed the structural strength limit causing wing damage. This aerodynamic effect is called flutter. The speed at which flutter occurs is cited as flutter speed. Flutter is the self-excited oscillation in which energy is absorbed by the lifting surface from the air stream [10]. When the structure flutters, it reaches an unstable state, and the oscillation condition diverges. When the aircraft speed is below the flutter speed, the flutter oscillation is always damped, thus it remains stable. The amplitude of vibration remains constant when the speed of an aircraft is equal to the flutter speed. Active flutter suppression is examined by using an automatic control system to actuate the control surfaces on the wing reacting to structural motion. The active flutter suppression changes the characteristics of the aeroelastic modes, and that, in turn, causes flutter to occur at a much higher flight velocity. However, while theoretical studies concerning active flutter suppression exist, flutter suppression still remains highly experimental.

## *2.3 Limit Cycle Oscillation:*

One of the contributions the Spring 2002 Active Wing group had on this continuous project is the research on Limit Cycle Oscillation. To summarize, Limit Cycle Oscillation is a limited-oscillating response of an aircraft that is caused by interactions between aircraft system forces. Unlike the oscillation amplitude in flutter which increases to infinity when the system becomes unstable, the oscillation amplitude in Limited Cycle Oscillation does not infinitely increase.

"The oscillation achieves a finite amplitude and cannot grow any larger due to some nonlinear limiting mechanism. These mechanisms destroy the ability of the forces to continue to grow in proportion to deflections, thus the mechanisms are nonlinear in nature." [9]

This implies the Limit Cycle Oscillation can cause cyclic flow separation over the wing during flight, which increases the angle of attack, therefore no longer generating more aerodynamic forces on the wing surfaces. Other nonlinear limiting mechanisms also occur in aircraft structure.

## Oscillating Flaps

Many lifting devices are used to increase the lift coefficient when aircraft fly at high angles of attack. However, conventional leading and trailing-edge static flaps do not enhance the lift or prevent the aircraft from stalling when it flies at a critical angle of attack. The oscillating flaps effect on lift coefficient is a new technique and has been studied recently. ATAK Technologies' proposed objective for this semester is to study this phenomenon.

The Active Wing Technologies group from Summer 2002 mentioned in their final report that the applications of oscillating flaps have helped control the separation of the flow over the wing surface. However, they concluded that the results are not the same for all flying conditions. Professor Dr. F.B. Hsiao at National Cheng Kung University in Taiwan has also been studying this subject matter, and he has written some technical reports as well. In one of his reports, Dr. Hsiao has indicated oscillating flaps create vortices that "enhance the momentum transfer between the free-stream and the boundary layer" and thus increases the "reattachment of vortices" [11].

During flight, there are two flow types that generate lift force to the wing; they are attached-flow type and detached-vortex-flow type. The difference in the circulations of upper and lower boundary layers in the attached-flow type generates the lift force near the quarter chord of the airfoil. In addition, rolled-up leading-edge vortices in the detached-vortex-flow type provides further lift to the airfoil. However, when a higher angle of attack is achieved to provide more lift, the vortices formed become uncontrollable through unsteady separation, vortex shedding, and vortex breakdown. Control of vortices is essential if higher angle of attack is to be reached without dynamic stall occurring. The two possible methods of controlling the vortices are flow separation control and flow reattachment control; these methods can be conducted at different stages of the vortex formation.

First, during a stage of vortex evolution, the vorticity strength is described by the boundary vorticity flux below, which represents the balance between pressure force, inertial force, and viscous force along the tangential direction. [12]

$$\sigma = n \times \rho a_b + (n \times \nabla) \cdot (\Pi \cdot I + \tau \cdot n) \qquad \text{Eq. 2.6}$$

where:

**n** → unit normal vector
$\mathbf{a}_b$ → solid wall acceleration
$\Pi = p - (\lambda + 2\mu)\nabla \cdot u$ → dynamic "compressing variable"
**I** → unit tensor
$\boldsymbol{\tau} = \mu\boldsymbol{\omega}' \times \mathbf{n}$ → skin friction
$\boldsymbol{\omega}' = \boldsymbol{\omega} - 2\mathbf{W}$
**W** → wall angular velocity
λ → second viscosity
μ → viscosity

Controlling the boundary vorticity flux controls the flow separation by using the possible methods shown below:

1.) Proper design of the airfoil or wing geometry, and application of suction and blowing to control tangential pressure gradient
2.) Modify the local **τ**-field near critical points, or application of local blowing or suction to control skin-friction field
3.) Introduce a local movable wall (e.g. an oscillating flap)

Secondly, flow separation should be controlled prior to the unfavorable formation of vortices due to separation from a smooth surface. "It is always less effective to alleviate an already formed stable vortex than to prevent its formation." [12] The enstrophy flux, which describes the steady separation from a smooth surface, is as follows:

$$\eta \equiv \mu \frac{\partial}{\partial n}\left(\frac{1}{2}\omega^2\right) = \omega \cdot \sigma = \frac{1}{\mu}\tau \cdot \nabla p + \mu\omega \cdot \nabla n \cdot \omega \qquad \text{Eq. 2.7}$$

Where $\eta > 0$ implies an enstrophy source, a newly formed vortex strengthens the existing one; while $\eta < 0$ implies a sink, where a newly formed vortex cancels the existing one. Because flow separation is indicated by a sink, it can be eliminated by sufficient suction near the separation. [12]

If a boundary layer is already separated, then control of its reattachment is needed. This is feasible using the unsteady surface excitations. Many configurations of basic two-dimensional wings were proposed to capture vortex, and thus achieve a sustainable high lift at high angle of attack. For example, a Kasper wing as shown in Figure 2.6 was successfully flight tested. However, in this example, the serious instability problem was noticed, (a large amount of jet blowing or suction was required to stabilize the captured vortex) and the crucial role of unsteadiness was ignored.

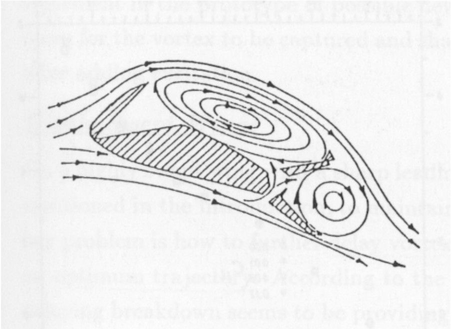


**Figure 2.6: Detached vortex flow on Kasper wing [12]**

Another approach which successfully suppressed separation by oscillating a flap tangentially near the separation point was proposed. The receptivity mechanism of the tangential oscillation mode is straightforward compare to acoustic excitation (a method that use acoustic wave to suppress separation). In the experiment conducted by Zhou and

Felnholz, the angle of attack and the lift increases up to $27^0$ and 60% respectively; when a small leading-edge oscillating flap was used it forced the shear layer, which was separated from the leading-edge, to attach back to the airfoil surface. Furthermore, the excitation frequency that yielded the highest lift coefficient for $\alpha = 27^0$ was obtained around 15 Hz. The relationship between the average velocities at both sides of the boundary layer ($\overline{U}$), the momentum thickness of the vortex layer ($\theta$), and the excitation frequency (f) is described by the equation below:

$$St = \frac{f\theta}{\overline{U}} = 0.032 \qquad [12] \qquad \text{Eq. 2.8}$$

In one of the works from Kobayakawa, Kondo, and Suzuki at Kyoto University in Japan, the flow behavior around the airfoil is proved to be controlled by the surface oscillation. The use of surface oscillation can enhance the lift force, and thus prevent leading edge stall of airfoil at high angle of attack. [15] One of the methods that generates surface oscillation is the use of Poly Vinylidence Flouride (PVDF) film on the airfoil surface. The PVDF has strong dielectric property under an electric field that produces a stress when polarization changes in an adverse direction. Figure 2.7 is an example of the configuration of the film embedded on the airfoil surface, and during the experiment, the film oscillates vertically at average amplitude of 11 $\mu m$ .

**Figure 2.7: NACA-0012 airfoil with surface oscillation. [15]**

From this experimental result, the lift coefficient and stall angle of attack increased in the oscillation condition. As seen from Figure 2.8, in a non-oscillated condition, maximum lift coefficient, $Cl_{max}$ was 0.72 and stall angle of attack was 14$^0$. However, in the oscillated condition, the maximum lift coefficient and stall angle of attack increased to 0.76 and 15$^0$ respectively. Furthermore, indicated from Figure 2.9, the maximum increment of $Cl_{max}$ was achieved around an oscillation frequency of 50 Hz.

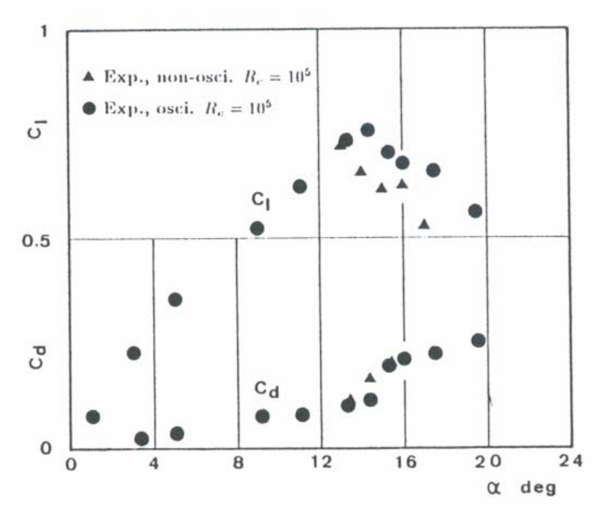


**Figure 2.8: Cl, Cd vs. α in the experiment at $Re = 10^5$. [10]**

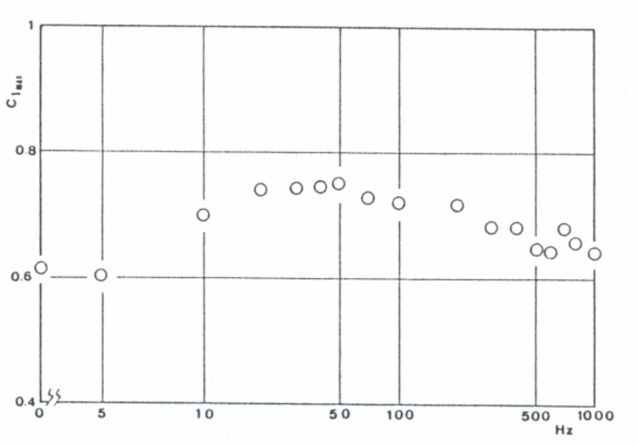


**Figure 2.9: $Cl_{max}$ vs. oscillation frequency in the experiment [10]**

The improvement of lift force was further explored in the numerical simulation. In the non-oscillated condition, the lift coefficient $C_l$ dropped from $Cl_{max} = 1.38$ ($\alpha=14^0$) to 1.15 at the stall angle of attack, $\alpha = 15^0$. However, in the oscillated case, although the lift coefficient could not exceed 1.38, it increased to 1.31 at $\alpha = 15^0$ as seen from Figure 2.10.

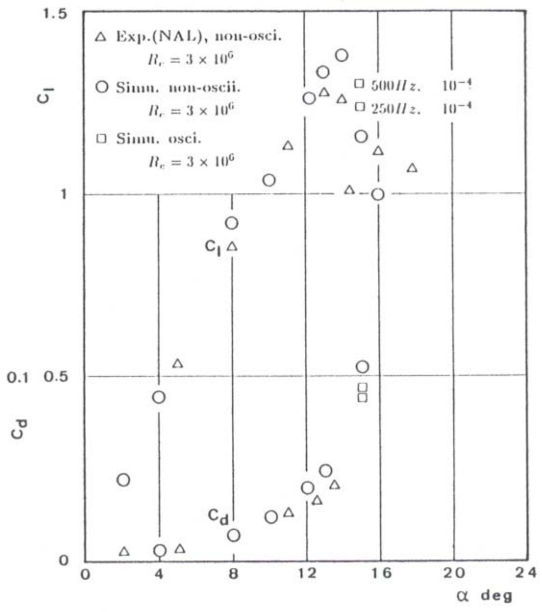
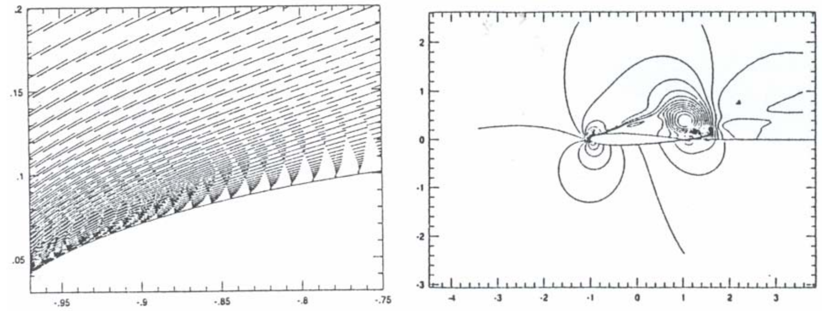
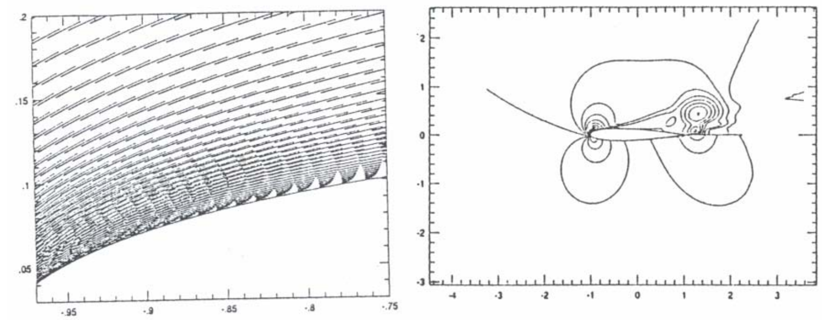


**Figure 2.10: Cl, Cd vs. α (Re = 3 x $10^6$) [15]**

The lift force decreased significantly for the non-oscillated case when compared to the oscillated case due to flow attachment which was enhanced by surface oscillation. Velocity vectors and density contour illustrated in Figure 2.11 implied that while a strong vortex is shed, and flow separates from the surface for a non-oscillated case, the flow stays attached to the surface and the vortex shed is relatively small for the oscillated case.



(a) Non-oscillated (a)· Non-oscillated



(b) Oscillated (b) Oscillated

**Figure 2.11: Density contours and velocity vectors ($\alpha = 15^0$, Re = $3x10^6$). [10]**

Because different Reynolds numbers were used in numerical simulation and wind tunnel testing, the comparison can be done only qualitatively. However, the effort to improve lift force at high angle of attack using surface oscillation was successful in both numerical simulation and wind tunnel testing. The lift coefficient increased and stall angle was delayed when surface oscillation is used. Furthermore, it may be presumed that the oscillation energy is proportional to the Reynolds number in order to control the separated flow completely. [15]

Another recent study was conducted by the University of Cincinnati Ohio (UCO) researchers Q. Deng and I. Gursul to test the effects of oscillating flaps on leading-edge vortices and vortex breakdown over a delta wing with upward-deflected flaps. These individuals ran different tests to compare the effects of stationary and oscillating leading-edge flaps on the breakdown location of vortices. Different flap angles were used to see the differences between the two types of leading-edge flaps. At oscillation flap amplitude,

$$\delta = 120^0 + 60^0 \sin wt \qquad \text{Eq. 2.9}$$

where $k = \omega c / 2U_\infty = 0.4$ and $\alpha = 30^o$,

"The oscillation of the flaps produces delay of breakdown in some part of the cycle compared to the quasi-steady case, but it also advances breakdown in other parts of the cycle." [16] In addition, at oscillation flap amplitude, $\delta = 90^0 + 10^0 \sin wt$, k = 0.4, and $\alpha = 20^o$, the breakdown location found at the trailing-edge of the wing, whereas for the stationary flap the breakdown location is over the wing. Another test was conducted within the same parameters as the previous test, but it used a higher angle of attack. The results indicated that the breakdown location did not change that much compared to the location at $20^0$. In conclusion, when the breakdown location occurs upstream of the trailing-edge region for the stationary flap, the oscillating flaps do not have any effects on the breakdown location. However, when the breakdown location occurs near the trailing edge region for the stationary flap, the effect of the oscillating flaps is greatest. The experiment conducted by Q. Deng and I. Gursul is relevant because it provides some facts about how oscillation flaps can affect the vortices. The flow downstream of the vortex breakdown is unsteady, which affects the stability of the aircraft. Vortex analysis needs to be researched to better understand the theory behind oscillating flaps.

In the case of a swept wing, rather than a basically two-dimensional wing discussed above, the focus of surface oscillation would be to delay vortex breakdown and maintain highly concentrated and stable leading-edge vortices. From Yao's vortex tube experiment, the spiral wave can delay bubble-type breakdown. [12] Also, the spiral wave can change the breakdown from bubble type to spiral type, where spiral types always occur further downstream than the bubble types, thus delaying the breakdown. [12]

Many experiments have been done that proves the effectiveness surface oscillation had on providing high lift coefficient at high angle of attack. The hypothesis is that using oscillating leading and trailing-edge flaps increases lift coefficient for aircraft that fly at a high angle of attack.